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ROCKET PROPELLANT PERFORMANCE AND ENERGY OF THE CHEMICAL BOND

By P. F. Winternitz[1] and D. Horvitz[2]

Symbols

g = acceleration of gravity (ft/sec^2)
m = mass flow rate (slugs/sec)
n = number of lb-moles
w = weight flow rate (lb/sec)
$\bar{C}_p$ = mean heat capacity at constant pressure (Btu/mole-deg)
$\bar{C}_v$ = mean heat capacity at constant volume (Btu/mole-deg)
γ = $\bar{C}_p/\bar{C}_v$ = ratio of mean heat capacities
F = thrust (lb)
ΔH° = heating value of propellants (Btu/mole)
$\Delta H'$ = heat required for heating products to combustion temperature and for dissociation (Btu/mole)
I_{sp} = specific impulse (sec)
$\bar{M}$ = mean molecular weight of combustion products (lb/mole)
R = universal gas constant (ft-lb/mole-° R)
T_c = chamber temperature (° R)
T_e = exhaust temperature (° R)
V_e = effective exhaust velocity (fps)
V_{max} = maximum exhaust velocity obtainable in theory (fps)

THE advent of rockets has brought about fundamental changes in the type of propellants being used in power plants and also in the evaluation of their relative merits.

In reciprocating engines, turbojets, ramjets, and other power plants, a fuel is burned with atmospheric or compressed air; but in rockets, propellant combinations, which include in liquid form all ingredients for combustion, are being used. This is the reason why rockets are the only power plants which can be operated outside of the atmosphere or at heights where there is practically no oxygen to sustain combustion of a fuel.

A high chemical energy is the main requirement for rocket propellants just as it is for fuels used in other power plants. However, the rocket permits a much higher concentration of energy than any other power plant because it has no moving parts in the combustion space itself and can,

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therefore, handle extremely high temperatures. For this reason new, so-called "high-energy" fuels can be utilized in rockets, the application of which to conventional power plants does not seem feasible at the present time.

Clearly, nuclear energy will ultimately be the source of the propulsive force in rockets since a much higher concentration of energy can be produced by nuclear reactions than by chemical reactions. But until it has been found possible to utilize nuclear energy the search will go on for compounds which will yield the utmost in chemically derived energy.

The amount of this energy can be determined for a new compound from the heat of combustion, from the specific heats, from the equilibrium constants of the gases produced by reactions, and from related chemical and physical properties.

It is the purpose of this paper to show that the heat of combustion of an unknown chemical compound is the essential quantity for the determination of its performance in a rocket and that this quantity can be computed with a high degree of accuracy from known values for the energy of chemical bonds.

A few remarks are pertinent before proceeding further. First, it is not claimed that the present paper is original. Especially in the section dealing with chemical-bond energies, the results of the work of K. Fajans, Linus Pauling, and other authors will be freely used. It is hoped the paper will show to practical engineers how the results of basic physical and chemical research can be applied directly to engineering problems.

Secondly, exactly the same or similar considerations as will be presented are applicable to the determination of the performance of power plants other than rockets. However, in rockets the application of new high-energy propellants which are not suitable for other power plants is indicated. Research on new rocket fuels is concerned with many unconventional compounds. Actual testing of these new compounds in rockets is extremely time-consuming and expensive. Even the experimental determination of the necessary data often causes considerable delay and difficulties. For these reasons a prediction of performance is especially desirable for rocket fuels.

A Few Fundamental Formulas of Rocket Theory

Rockets are internal combustion engines utilizing the reaction experienced by the motor structure due to the ejection of high velocity matter from the high-pressure combustion chamber into the considerably lower pressure surroundings. This reaction generates a thrust in a direction opposite to the ejected matter. The thrust, according to fundamental laws of mechanics, is equal to the change in momentum in unit time of the ejected matter. That is,

$$F = mV_e = \frac{w}{g} V_e \quad [1]$$

where F is the thrust, m is the mass flow per unit time, w is the weight flow per unit time, V_e is the effective exhaust velocity of the ejected gases, and g is the acceleration of gravity, all in consistent units. It is assumed that the matter inside the rocket is initially at rest—which is nearly true.

A most important quantity for evaluating the performance of a rocket propellant combination (and the only one with which this paper is concerned) is the ratio of delivered thrust to rate of propellant consumption. If the rate of propellant consumption is expressed in weight units, the ratio is called the "specific thrust" or (less accurately but more generally) the "specific impulse":

$$I_{sp} = \frac{F}{w} \quad [2]$$

If the rate of propellant consumption is expressed in mass units, the ratio is called the "effective exhaust velocity":

$$V_e = \frac{F}{m} = \frac{F}{w/g} \quad [3]$$

I_{sp} and V_e are connected by the equation:

$$V_e = I_{sp} \cdot g \quad [4]$$

In textbooks on fluid mechanics and on thermodynamics it is shown that the maximum theoretical exhaust velocities of an ideal gas at the initial temperature T_c escaping through a converging-diverging nozzle into a vacuum is given by the equation:

$$V_{max} = \sqrt{\frac{2g\gamma}{\gamma - 1} \frac{RT_c}{\bar{M}}} \quad [5]$$

where g is the acceleration of gravity, γ the ratio of the mean specific heats, R the universal gas constant, and $\bar{M}$ is the (mean) molecular weight of the gas.

This formula is based on the assumption that the random thermal motion of the gas is completely converted into directed kinetic energy of the escaping molecules.

Actually only a portion of this velocity can be obtained in practice by the expansion to pressures and temperatures above zero, because according to the second law of thermodynamics only the fraction

$$\eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1} \quad [6]$$

can be converted into kinetic energy, if the temperature of the carrier drops from the temperature T_1 to the temperature T_2. In the present case T_1 is the chamber temperature T_c and T_2 is the exhaust temperature T_e. It is convenient to replace in Equation [6] the unknown ratio of chamber and

exhaust temperature (T_c and T_e) by the known ratio of chamber and exhaust pressure by means of the law for the adiabatic expansion of an ideal gas. If this is done the expression for the fraction of heat available for conversion into kinetic energy becomes

$$\eta = 1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma - 1}{\gamma}} \quad [7]$$

Multiplying the formula for the maximum exhaust velocity by this factor yields Zeuner's expression for the effective exhaust velocity

$$V_e = \sqrt{\frac{2g\gamma}{\gamma - 1}\frac{RT_c}{\bar{M}}\left(1 - \frac{P_e}{P_c}\right)^{\frac{\gamma - 1}{\gamma}}} \quad [8]$$

This formula contains besides universal constants the following quantities: The mean molecular weight and the mean ratio of the specific heats of the products of combustion, the chamber and the exhaust pressure, and the chamber temperature.

Importance of Heat of Combustion for Performance Calculations

The chamber and exhaust pressure are simply operating conditions. Mean molecular weight and mean ratio of specific heats of the reaction products could be determined in a straightforward way from the operating conditions and from existing extensive tabulations, provided the chamber temperature were known. It could be done because the products of combustion are practically without exception simple compounds such as water, carbon dioxide, nitrogen, hydrogen, and so on, the physical properties of which have been carefully determined at all required temperatures. Therefore, the problem of evaluating the equation for the exhaust velocity reduces to the determination of the chamber temperature. This temperature enters explicitly into the formula and in addition determines also the numerical values to be used for the properties of the reaction products. It is the most important single quantity in the formula for the exhaust velocity. Now the chamber temperature can be calculated from the heat of combustion of the fuel in the following way.

Assume that a propellant combination (fuel plus oxidizer) evolves on combustion $\Delta H°$ Btu of energy per lb-mole (heating value based on absolute zero as the reference temperature). Assume also that of this energy an amount $\Delta H'$ is used for cooling the propellants to the reference temperature, for changes in state and for dissociation of the combustion products. An amount of $\Delta H° - \Delta H'$ Btu will then be available per lb-mole of reactants, for heating the reaction products. One mole of the products of combination with an average heat capacity $\bar{C}_p$ requires $\bar{C}_p T_c$ calories in order to be heated from absolute zero to the combustion temperature T_c. But due to the chemical reaction and to dissociation one

mole of propellant gives, on combustion, a different (usually higher) number of moles.[3]

Therefore, in order to arrive at the heat required to raise the combustion products to the equilibrium temperature T_c, the expression $\bar{C}_p T_c$ has to be multiplied by the number n of moles of combustion products formed from one mole of propellant.

Now the combustion temperature is clearly given by the condition that the heat absorbed in heating the products of combustion is equal to the heat developed by the combustion.

This can be expressed by the equation

$$n\bar{C}_p T_c = \Delta H^\circ - \Delta H' \quad [9]$$

or

$$T_c = \frac{\Delta H^\circ - \Delta H'}{n\bar{C}_p}$$

This equation shows that the chamber temperature can be calculated from the heat of combustion and the known properties of the combustion products.

The actual computations are rather involved. As has been indicated before, ΔH° has to be referred to absolute zero (or other equivalent corrections must be made). Also, ΔH° has to take into account variations in the enthalpy of the propellants due to changes in state, such as heats of evaporation and so on. Furthermore, as discussed before, the heat available is $\Delta H^\circ - \Delta H'$, which is only a fraction of the heating value ΔH° of the fuel. The amount of this fraction, the number of moles of combustion product formed from one mole of propellants and their average specific heat have to be calculated from the chemical composition of the combustion products with the aid of tabulated data and by complicated methods.

But in principle, knowledge of the heat of combustion is the only requirement for the evaluation of propellant performance in a rocket with known operating conditions—no matter how complicated the actual procedure may be.

Therefore, knowledge of the heat of combustion completes the set of data necessary for the theoretical evaluation of the formula for the exhaust velocity.

But this figure is not always available for new fuels and therefore one has to resort in such cases to an evaluation from data based on the concept of the chemical bond.

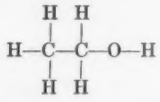
Concepts of the Chemical Bond and of Bond Energies

The concepts of chemical bonds and chemical bond energies are based on

[3] For example, in the combustion of alcohol vapor, $C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$, five moles of products are formed from four moles of propellants. In addition, the number of five is further increased because at high temperatures carbon dioxide and water dissociate into smaller molecules such as CO, O_2, OH, H_2, and so on.

the fact that the atoms constituting a molecule are arranged in certain stable patterns, so-called structures, in which the atoms are kept in definite positions with respect to each other by directed chemical forces, the valence forces. This fact, which has been established by chemists beyond doubt long ago, is expressed briefly by saying that chemical bonds link the atoms in a molecule.

For example, ethyl alcohol with the formula C_2H_6O has the structure



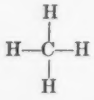
and according to this structure the carbon atom to the left is permanently linked to three hydrogen atoms and to one carbon atom. This situation is expressed by stating that it has three carbon-hydrogen and one carbon-carbon bond. Similarly the second carbon atom has two carbon-hydrogen, one carbon-carbon, and one carbon-oxygen bond, whereas the oxygen has one oxygen-carbon and one oxygen-hydrogen bond.

The formation of these bonds is clearly due to certain directed attractive forces between the atoms.

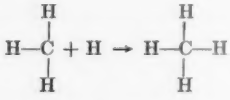
According to fundamental principles of physics, work is done and a certain amount of energy is therefore liberated, when a chemical bond is formed. This energy appears as heat of the reaction creating the chemical bond.

Conversely "bond energy" can also be defined as the energy which must be absorbed to break a bond between two atoms with the production of neutral atoms.

In order to arrive at well-defined values for the bond energy the assumption has to be made that the same amount of energy is liberated whenever the same bond is formed. This assumption is by no means self-evident, as is readily seen by considering a simple compound such as methane, CH_4. Methane has the structure



What is being claimed is that the amount of energy liberated is the same when the first hydrogen atom is linked to carbon to form the radical C—H, as when the last hydrogen atom is added by the reaction



In other words, it is claimed that there is no interference between the four

centers of attraction in the carbon atom. This can obviously not be strictly the case. But it is very nearly true in many instances and this concept of the "additivity of chemical bond energies" has proved to be a good working hypothesis. If this hypothesis is accepted, then the heat of formation of any compound is the sum of the energies of all its chemical bonds.

The heat of formation of alcohol should therefore be the sum of seven C—H, one C—C, one C—O, and one O—H bond. It will be seen later that this is very closely correct.

It will therefore be assumed for the moment that the heat of formation for all possible compounds can be computed from their chemical bond energies and that all chemical bond energies are known. With this assumption, the heat of combustion of any compound with a known structure can be computed without any trouble from the known heat of combustion of the elements from which the compound is formed. This can be easily shown by elementary considerations based on the law of conservation of energy.

Nature of the Chemical Bond

Now the energies being liberated in the formation of chemical bonds depend very much on the type of atoms involved. This fact indicates a close relation between chemical bonds and the structure of atoms. This connection has been realized by chemists and physicists for a long time. Some more or less hazy ideas existed in the minds of scientists specifically concerning the relation of such bonds to electric charges inside the atom. However, this relation was clarified sufficiently for application to chemical bond energies only when a satisfactory atom model had been proposed.

Such a model was first suggested by Rutherford in order to explain radioactive phenomena; it was later very much improved, especially by N. Bohr in connection with spectroscopic phenomena.

The Rutherford-Bohr atom model cannot explain all the results of modern refined measurements. But it is still a useful means to visualize what is actually happening between atoms and in molecules if one wishes to avoid complicated mathematics and abstract philosophical concepts on which wave mechanics is based.

According to the Rutherford-Bohr model, an atom consists of a positively charged nucleus, which carries practically all the mass of the atom and of a number of negatively charged particles, electrons, rotating at extremely high speed around the nucleus. All the electrons surrounding the nucleus have the same charge, the sum of which equals just the positive charge of the nucleus to give an electrically neutral atom. The chemical properties of an atom are determined by the number and configuration of the electrons, which are arranged in different layers or shells around the nucleus. These shells are filled successively when the number of electrons

is increased as we proceed to heavier elements with more electrons. Only electrons in incompleted shells, so-called valence electrons, participate in normal chemical reactions. Elements containing only completed shells, the noble gases, are therefore chemically inert. It is readily seen that elements with the same number of electrons in incompleted shells (valence electrons) will have similar chemical properties. This fact is the basis for the arrangement of the chemical elements in a periodic table.

For the present purpose it is only interesting how these concepts contribute to the understanding of chemical bonds. The stability of an electronic arrangement which contains only completed shells has been mentioned before. From this fact, it may be inferred that in chemical combinations atoms tend to acquire this stable configuration, or what amounts to the same, tend to acquire the inert gas structure.

This tendency toward formulation of completed electron shells can be satisfied fundamentally in two different ways.

In the first case the necessary number of electrons is released or taken up by the atoms so as to give electrically charged particles, ions. The sign of the change depends on the way in which the stable configuration is reached. The alkali metals, for instance, reach the noble gas configuration if an electron is given up, and form thus a positively charged metal ion; the contrary is true for the halogens.

As an example, the formation of the salt sodium fluoride from the alkali metal sodium and the halogen fluorine can be represented in the following way:

$$:\ddot{\mathrm{N}}\mathrm{a}:\cdot + \cdot\ddot{\mathrm{F}}: \xrightarrow[\text{transfer}]{\text{electron}} :\ddot{\mathrm{N}}\mathrm{a}:^{+} + :\ddot{\mathrm{F}}:^{-}$$

Here the dots represent electrons with a negative charge. Sodium, represented by the symbol Na, has one extra outer electron besides a completed shell formed by the stable octet consisting of eight electrons. On the other hand, fluorine, represented by the symbol F, lacks just one electron for this same stable configuration. Therefore, sodium can transfer its excess electron readily to fluorine and both atoms attain through this transfer the stable electron configuration. Sodium becomes in this way positively charged and fluorine negatively. Thus two oppositely charged ions are formed which are strongly attracted by electrostatic forces. The resulting chemical bond, which is characteristic for salts, has been named an ionic bond. It is also seen that an estimate of the strength of this bond should be possible if certain data, such as atomic distance, arrangement of the ions in a crystal lattice, etc., are known. Similar considerations hold for most inorganic salts, which are formed by the combination of elements which have to lose or gain only a limited number of electrons—usually not more than one or two—in order to arrive at the stable electron configuration in the outer electron shell.

The same explanation does not hold for the formation of chemical bonds, where elements are involved which cannot reach readily the stable electron configuration because too many electrons would have to be transferred. Nevertheless, the fact that such elements can form strong bonds can be explained, following G. N. Lewis,[4] by assuming that the stable noble gas configuration is reached by sharing of electrons in pairs.

For example, the formation and electronic structure of methane is represented according to this concept, which has been fully verified by experiment as follows:

$$\cdot\dot{C}\cdot + 4\cdot H \rightarrow H{:}\ddot{\underset{\ddot{H}}{\overset{H}{C}}}{:}H$$

Again, each dot represents an electron and it is readily seen that the carbon atom is surrounded by eight electrons forming the stable configuration of an octet and each hydrogen atom is surrounded by two electrons which give the stable electron shell pertaining to this element. Also, the concept of sharing of electrons in pairs becomes clear from this presentation. Each one of the electrons belongs to the carbon as well as to the hydrogen atoms. Obviously, no change in the charge of an atom occurs in this case, and therefore, no ions are formed. This type of bond is the second fundamental type of chemical bonds; it is called the covalent bond and is common in organic compounds, which form the overwhelming majority of possible fuels. Therefore, the covalent bond is of particular interest for the present case.

It will be readily understood that the presentation given is oversimplified and that transition stages, and bonds intermediate between the ionic and covalent bond should be quite common. This is actually the case and the exact mathematical determination of the contribution of both types of bonds to the resulting linkage causes considerable difficulties, even for such simple configurations as the hydrogen molecule. But it would lead too far to enter deeper into these interesting developments. The short excursion into the field of atomic structure had only the purpose to give some idea of the nature of the strong forces which hold the molecules together.

Determination of Chemical Bond Energies

It will now be indicated how the chemical bond energies resulting from these forces can be determined. This determination is based on results obtained from both atomic theory and thermochemical measurements. The actual magnitudes of chemical bond energies have been compiled in tables by different authors.

Table 1, taken from the book "The Nature of the Chemical Bond," by Linus Pauling, gives the energy of different single covalent bonds,

[4] G. N. Lewis, "The Atom and the Molecule," *Journal of the American Chemical Society*, vol. 38, 1916, p. 762.

that is, bonds where only one pair of electrons is being shared. Values are given in kcal/gm mole and are referred to the "standard states" at 291 K and 1 atm pressure. As can be seen, most of the common single bonds are included.

TABLE 1 ENERGY VALUES FOR SINGLE BONDS[a]

Bond	Bond energy (kcal/mole)	Bond	Bond energy (kcal/mole)	Bond	Bond energy (kcal/mole)
H—H	103.4	O—H	110.2	Si—I	51.1
C—C	58.6	S—H	87.5	Ge—Cl	104.1
Si—Si	42.5	Se—H	73.0	N—F	68.8
Ge—Ge	42.5	H—F	147.5	N—Cl	38.4
N—N	20.0	H—Cl	102.7	P—Cl	62.8
P—P	18.9	H—Br	87.3	P—Br	49.2
As—As	15.1	H—I	71.4	P—I	35.2
O—O	34.9	C—Si	57.6	As—Cl	60.3
S—S	63.8	C—N	48.6	As—Br	48.0
Se—Se	57.6	C—O	70.0	As—I	33.1
F—F	63.5	C—S	54.5	O—F	58.6
Cl—Cl	57.8	C—F	107.0	O—Cl	49.3
Br—Br	46.1	C—Cl	66.5	S—Cl	66.1
I—I	36.2	C—Br	54.0	S—Br	57.2
C—H	87.3	C—I	45.5	Se—Cl	66.8
Si—H	75.1	Si—O	89.3	Cl—F	86.4
N—H	83.7	Si—S	60.9	Br—Cl	52.7
P—H	63.0	Si—F	143.0	I—Cl	51.0
As—H	47.3	Si—Cl	85.8	I—Br	42.9
		Si—Br	69.3		

[a] Pauling, "The Nature of the Chemical Bond," p. 53.

Following Linus Pauling, the determination of the value of the O—H bond will be discussed as an example for the method used. This value is derived from data collected for water and its constituents, hydrogen and oxygen. If the formula for water H_2O is written in the more detailed form

it is seen that it contains two O—H bonds, and that it is composed of two single hydrogen and one single oxygen atom. (The formula for water has not been written by accident in the way it is shown. As a matter of fact, the angle included by the two bonds, the distances of the atoms and similar quantities have been measured accurately.)

Now the reaction by which water is formed from hydrogen and oxygen atoms can be assumed to take place in two steps: First, the hydrogen and oxygen atoms combine to form hydrogen and oxygen molecules and then the hydrogen and oxygen molecules combine to form water. Accordingly, the heat of formation of water from the atoms is the sum of two quantities: First, the energies which are liberated when the hydrogen and oxygen

molecules are formed from hydrogen and oxygen atoms, and secondly, the heat of reaction, when hydrogen and oxygen molecules combine to give water.

This situation can be expressed in symbols as follows:

$2H \rightarrow H_2$	—103.4 kcal/mole	1st step—molecules from atoms
$O \rightarrow \frac{1}{2}O_2$	— 59.1 kcal/mole	
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	— 57.8 kcal/mole	2nd step—water from molecules
$2H + O \rightarrow H_2O$	—220.3 kcal/mole	Result: Water from atoms

Thus, 220.3 kcal/mole are evolved, when two O—H bonds are formed.

If these two bonds are assumed to be equivalent, one-half of this figure can be simply taken as the energy of the O—H bond. The value of 110.1 kcal/mole has accordingly been inserted into the table of the single bonds. The meaning of the assumption of equivalence of the two O—H bonds may become somewhat clearer from the following symbolic presentation:

$$\Delta H \left[\begin{array}{c} H + O \\ \downarrow \\ H{-}O \end{array} \right] \equiv \Delta H \left[\begin{array}{c} H{-}O{+}H \\ \downarrow \\ H{-}O{-}H \end{array} \right]$$

It is seen that it is assumed that the same energy ΔH is liberated, when one hydrogen atom is combining with one oxygen atom to give the hydroxyl radical O—H, as when one hydrogen atom combines with the hydroxyl radical, OH, to give water H—O—H.

Quite similar methods are used for other bonds. For example, the heat of formation of methane, CH_4, is used in combination with the energy required to break up the hydrogen molecule into atoms for the evaluation of the energy of the C—H bond.

The assigned quantities, as shown in Table 1, are based on the assumption of the additivity of bond energies which has just been discussed. Actually this hypothesis is only true if certain types of energy other than electronic energy are excluded from the values assigned to the bond energy. The contributions made by these types of energies, such as translational, rotational, and vibrational energy are, however, small in comparison to the contribution of the electronic energy. As it has been pointed out before, it is specifically not quite true that equal bond energies can be assigned to equal bonds in the same molecule.

In the calculation of the strength of the O—H bond three energy values had to be used. The last one, the heat of formation of water from the hydrogen and oxygen molecules, is found simply by calorimetric measurements, which have been carried out ever since theoretical chemistry became an exact science. However, the first and the second figure, representing the energy required to dissociate the hydrogen and oxygen molecules into the atoms, are derived from very refined spectroscopic measurements with the aid of wave-mechanical atom models. In general, accurate thermochemical data are available for more complicated molecules, whereas bond

energies for simple but very stable molecules must be calculated from spectroscopic measurements.

It is, therefore, seen that a correct atom model was not only necessary to visualize chemical bonds but also for the assignment of definite numerical values to these bonds.

It is also seen that the determination of the strength of bonds even in such simple molecules as hydrogen or nitrogen is quite a formidable task and therefore Table 2, which shows the heat of formation of the elements in their standard state from the monatomic gases, should be regarded with considerable respect. The values for the H—H bond and the O—O bond appearing in this table have been used for the calculation of the strength of the O—H bond.

TABLE 2 HEAT OF FORMATION OF ELEMENTS IN STANDARD STATES FROM MONATOMIC GASES (IN KCAL/MOLE)[a]

Element	Heats of Formation (kcal/mole)	Element	Heats of Formation (kcal/mole)
H	51.7	N	85.1
Li	39.0	P	31.6
Na	25.9	As	30.3
K	19.8	O	59.1
Rb	18.9	S	66.3
Cs	18.8	Se	61.0
C	124.3	F	31.8
Si	85.0	Cl	28.9
Ge	85.0	Br	26.9
Sn	78.0	I	25.6

[a] Pauling, "The Nature of the Chemical Bond," p. 54.

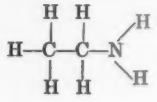
Calculation of Heats of Combustion from Bond Energies

Conversely this table together with the table for single-bond energies (Table 1) permits a rather close calculation of the heat of formation, or what amounts to the same, of the heat of combustion of a compound for which experimental data are not available.

At first the application of atomic bond energies to the theoretical calculation of heats of formation will be illustrated by one example, and then calculated and experimental values of heats of formation and combustion will be compared by means of a short table.

The theoretical calculation of the heat of formation of ethylamine, $C_2H_5NH_2$ will be used as the example.

The structural formula of ethylamine is



It consists of seven hydrogen, two carbon, and one nitrogen atoms and it contains, as can be seen from the structural formula, 5 carbon-hydrogen, 1 carbon-carbon, 1 carbon-nitrogen, and 2 nitrogen-hydrogen bonds.

Using Table 1 for the single-bond energies and Table 2 for the heats of formation of the elements in their standard state from monatomic gases, the set of values given in Table 3 is obtained:

TABLE 3 HEAT OF FORMATION OF ETHYLAMINE

Bond energies		Atomic heats of formation	
5C—H = 5 × 87.3 =	436.5 kcal/mole	7H = 7 × 51.7 =	361.9 kcal/mole
1C—C = 1 × 58.6 =	58.6 kcal/mole	2C = 2 × 124.3 =	248.6 kcal/mole
1C—N = 1 × 48.6 =	48.6 kcal/mole	1N = 1 × 85.1 =	85.1 kcal/mole
2N—H = 2 × 83.7 =	167.4 kcal/mole		
	711.1 kcal/mole		695.6 kcal/mole

The first term, at the left-hand side of the table, is the sum of the energies liberated on formation of all the chemical bonds in the compound from the atoms.

The second term, at the right-hand side of the table, comprises the energies required to form the atoms of the compound from the respective molecules in their standard states. In the present case, hydrogen and nitrogen atomic gas have to be formed from hydrogen and nitrogen molecular gas and gaseous atomic carbon has to be formed from solid graphite.

The difference between the two columns is 15.5 kcal/mole. This figure has to be corrected for the heat of evaporization in order to arrive at the theoretical value for the heat of formation of liquid ethylamine. The figure of 16.2 kcal/mole, which is thus obtained differs from the calorimetric value of 19.6 kcal/mole by an amount of 3.4 kcal/mole. The absolute and especially the relative difference between the theoretical and the experimental value appears at first sight to be very high.

But if it is remembered that the heats of formation are obtained by subtracting two large figures from each other, this result is not surprising. Rather too close an agreement would be fortuitous.

As a matter of fact, the objection that a small figure is obtained as the difference of two large figures can also be raised against experimental values of heat of formation which are based practically without exception on calorimetric measurements of heats of combustion. For some compounds the errors in the experimental figures may be just as great as those for the theoretical values.

For the present purpose only the energy is of interest, which is released when the compound, in this case ethylamine, is burned.

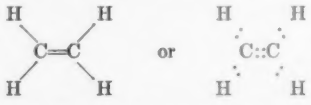
As has been pointed out before, this figure can be computed quite readily by using the heat of formation and applying the law of conservation of energy; extremely accurate figures for the formation of water and carbon dioxide from the elements are available for this purpose.

If the computation is carried out, the heat of combustion based on bond energies is found to be 405.2 kcal/mole. This figure compares favorably with the experimental value of 408.5 kcal/mole.

It follows, therefore, that the theoretical tables for chemical bond energies are a useful tool for the evaluation of fuels, even if they are sometimes not accurate enough to draw far-reaching theoretical conclusions.

So far only single bonds have been discussed which represent the simplest possible case. Only a few brief remarks on other types of bonds will be added.

In many organic compounds atoms are linked by double and triple bonds; such bonds are common between two carbon atoms, a carbon and an oxygen atom, or a carbon and a nitrogen atom. They are formed, when more than one pair of electrons is shared between two atoms. Ethylene, C_2H_4, for example, has a double bond between the carbon atoms and can be represented by the formula



the double bond being indicated by four dots. Acetylene, C_2H_2, has a triple bond and can be represented by the formula

H—C≡C—H or H:C:::C:H

the triple bond being shown by six dots. As has been postulated before, the hydrogen and the carbon atoms are surrounded by two and eight electrons, respectively, provided the shared electrons are counted on both atoms.

The energy of such multiple bonds cannot be computed simply by multiplying the single-bond values with the corresponding number, a condition which was clear to chemists many years before tables for bond energies were computed.

For this reason, separate tables have to be prepared for multiple bonds. As an example of such tables, a set of values taken from Pauling's book is shown below which will give an indication of the actual situation.

TABLE 4 VALUES OF BOND ENERGIES FOR MULTIPLE BONDS[a]

Bond	Bond Energy (kcal/mole)	Compounds
C=C	100	
C≡C	123	
C=O	142	Formaldehyde
C=O	149	Other aldehydes
C=O	152	Ketones
C=N	94	
C≡N	144	Hydrogen cyanide
C≡N	150	Other cyanides
C=S	103	
O=O	96	Δ state of O_2
N≡N	170	Normal N_2

[a] Pauling, "The Nature of the Chemical Bond," p. 131.

Using this table, the heat absorbed in the formation of propyne, C_3H_4, which contains a triple bond, has been computed to be 48.9 kcal/mole as compared to the calorimetric value of 45.1 kcal/mole. The difference of 3.8 kcal/mole becomes rather insignificant, when the heat of combustion is computed as has been pointed out before.

Similar calculations can be carried out for many other compounds and fairly accurate results for the heats of combustion are obtained, as can be seen from the last table which gives a comparison between calculated and experimental values for a few simple compounds.

TABLE 5 HEAT OF FORMATION

Compound		(kcal/mole)		(kcal/mole)	
Formula	Name	Calculated[a]	Experimental[b]	Calculated[a]	Experimental[b]
C_2H_5OH	Ethanol (l)	67.6[c]	65.3	325.3	327.6
$C_2H_5NH_2$	Ethylamine (l)	16.2[c]	18.6	410.9	408.5
$(CH_3)_3N$	Trimethylamine (l)	13.7[d]	10.7	575.6	578.6
$CH_3C{\equiv}CH$	Propyne (g)	48.9	46.5	467.5	465.1
$CH_2F \cdot CH_2OH$	2-fluoroethanol (g)	97.0	97.0	292.4	292.4

[a] Based on values of bond energies and heats of formation of the elements from the monatomic gases as given in Pauling, pp. 53, 54.

[b] Experimental data on heats of combustion from "Handbook of Chemistry," N. A. Lange, 1949. The heats of formation were calculated from these data using the values for CO_2 (g) and H_2O (l) given in "Selected Values of Chemical Thermodynamic Properties," National Bureau of Standards, Dec. 31, 1947.

[c] The heats of vaporization were obtained from data in "Selected Values of Chemical Thermodynamic Properties," National Bureau of Standards, Dec. 31, 1947.

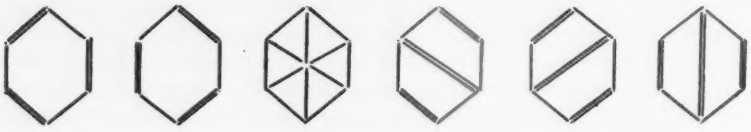
[d] The heat of vaporization was estimated by means of Trouton's Rule.

The difference between calculated and experimental values for the heat of combustion exceeds in no case one per cent, with the result that performance calculations based on these calculated values will be within one-half per cent of results obtained with the use of experimental values.

By now it may appear that heats of combustion for all possible compounds can be computed simply by looking up a few tabulated values for bond energies. However, the actual situation is somewhat more complicated and the tables for bond energies presented above are accurate only for fairly simple compounds.

Specifically, the application of bond energy values is limited to molecules to which definite bonds can be assigned unequivocally, a condition which is by no means always met. Another inspection of the table for multiple bonds will give an idea of the possible complications. It is seen that several different values for the double bond between carbon and oxygen had to be listed depending on the type of compound. This has been explained by resonance phenomena, which are more accentuated with double than with single bonds.

The concept of resonance implies in essence that a number of different bonds can exist in the same molecule. Benzene, for instance, contains no less than six different bonds. While the atoms themselves are fixed in their position, the binding electrons oscillate between the various positions indicated by the following representation.



VARIOUS BONDS OF BENZENE

It can be shown by a wave mechanical treatment that the combination of these six structures results in a lower energy content (higher average bond strength) than is to be assigned to any single configuration. Also, linkages between groups of atoms require special evaluation.

In addition, the absolute values to be assigned to certain fundamental bonds are not accurately known. There exists especially considerable disagreement among different scientists with respect to the value of the C—C bond, which is derived from the heat of sublimation of graphite, the exact determination of which causes great experimental difficulties.

Fortunately, knowledge of all absolute values of bond energies is not necessary for the calculation of reaction heats; rather it is only required that the set of data used is consistent.

In the present paper the data given in Pauling's book, "The Nature of the Chemical Bond," have been chosen. As has been seen, these data give fairly accurate results. But there are quite a number of different sets of data, which are also consistent and might have been chosen just as well.

But whatever set is selected it can be stated in general that available information on chemical bond energies will give satisfactory results provided proper care is taken in the application of a consistent set of data.

Conclusion

The problem to predict the performance of a propellant from its chemical bond energies has, therefore, been solved in principle, although many details have still to be worked out.

One final remark will throw some light on information which can be derived from bond energies in addition to the calculation of heats of reaction.

As has been seen, the heat evolved in a chemical reaction can be computed by assuming that the original compounds, the reactants, are at first disrupted into the atoms and that subsequently the atoms combine to form the reaction products. This picture does not, of course, describe the actual course of the reaction, but it gives the over-all energy balance.

Now an inspection of the tables presented reveals that a carbon-nitrogen bond with 48.6 kcal/mole bond energy causes less energy loss on breaking than a carbon-oxygen bond with 70.0 kcal/mole bond energy. Equally, a nitrogen-hydrogen bond with a bond energy of 83.7 kcal/mole is weaker than an oxygen-hydrogen bond with 110.2 kcal/mole. Also the energy of the double bond between carbon and carbon is less than twice the bond energy of the carbon-carbon bond.

It is, therefore, possible to draw quite general conclusions, such as, that amines containing the nitrogen-hydrogen and carbon-nitrogen bonds will perform better than the corresponding alcohols which contain the carbon-oxygen and oxygen-hydrogen bonds, and also that compounds containing a double bond are under the same conditions better propellants than compounds containing only single bonds.

Accordingly, it should be clear that a careful study of chemical bond energies will be extremely useful to everybody interested in the search for new and more powerful propellants. He will find by his study not only means of predicting the performance of hitherto unknown fuels and oxidizers, but he will also be safely guided in his search for better propellants.

It may appear somewhat unexpected that such far-reaching conclusions can be drawn from theory in a field so eminently practical as rocketry. But this fact is well in line with the ultimate goal of all exact science, which is to predict from a few basic concepts the outcome of new experiments and to forecast the result of new situations and conditions. No lesser man states this than E. Mach, who is well known for his aerodynamical investigations but possibly not so well known for his contributions to natural philosophy. The prediction of performance of rocket propellants from their chemical bond energies is certainly an encouraging step toward this goal of science.

✦ ✦ ✦

THE United States and other non-Iron Curtain countries are increasing research effort to develop more powerful jet engines because the Korean War has shown that the Russian MIG-15 can outdistance the fastest U.S. inceptor in its class.

In this country there are three jet engines in the 5500 to 6500 lb thrust range either undergoing service tests or in production. They are: Allison J-33 (400-D12) rated at 6350 lb of thrust (in service test stage); Pratt & Whitney J-48 at 6250 lb; and General Electric J-47 rated at 5500 lb.

According to the CADO *Technical Data Digest*, April, 1951, centrifugal-type jet engines, because of great bulk and large diameters are not considered ideal for structural changes and installations. Since greater power means addition of more compressor and turbine stages, the increase will mean greater engine bulk and frontal area. Axial type engines however can be expanded axial-wise to produce greater compression ratios without materially increasing frontal areas.

THROTTLING THRUST-CHAMBER CONTROL

By Marvin Meyer

Member ARS, Supervising Project Engineer, Rocket Department, Propeller Division, Curtiss-Wright Corporation, Paterson, N. J.

IN ROCKET power-plant installations for aircraft as well as for other types of power-plant installations, the desirability of having variable thrust control can be readily appreciated. Up to the present time, variable thrust from rocket power plants has not been generally available except in rather large increments obtained from firing one or more thrust chambers. In the case of solid fuels contained within the thrust chamber, burning rates are not readily controllable in a manner suitable for variable thrust operation. Powdered fuels or a means of mechanically injecting solid propellants could conceivably be developed. With liquid propellants, control of these factors is more easily accomplished. Throttled thrust-chamber operation requires that several factors be given special consideration. Some of these are: (1) Combustion chamber performance; (2) injector performance; (3) control of pump input power; and (4) the method of obtaining propellant-flow control.

Symbols

F	= thrust
P	= pressure
A	= area
W	= flow
γ	= ratio of specific heats

Subscripts

e	= nozzle exit
c	= chamber
th	= throat
a	= ambient
d	= design
ta	= tank
li	= inlet lines to pumps
lo	= outlet lines from pumps
p	= pumps
cv	= control valve
i	= injector

The thrust from a rocket motor is developed from two basic effects: (*a*) The change in momentum of the system, i.e., rate of propellant consumption times exit velocity. (*b*) The pressure differential existing across the exit face, i.e., exit pressure minus ambient pressure times the exit area. The equation for thrust in terms of pressure including these effects is:

$$F = P_c A_{th} \sqrt{\frac{2\gamma^2}{\gamma - 1}\left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/(\gamma-1)}\left[1 - \left(\frac{P_e}{P_c}\right)^{(\gamma-1)/\gamma}\right]} + (P_e - P_a)A_e \quad [1]$$

Assuming constant combustion temperature and constant mixture ratio, the terms under the radical become constant (i.e., γ is constant and P_e/P_c is a function of nozzle dimensions). The following nondimensional equation for thrust can then be written in terms of design conditions.

$$\frac{F}{F_d} = \frac{P_e}{P_{cd}}\left(1 + \frac{P_{cd}A_e}{F_d}\right) - \frac{P_a A_e}{F_d} \quad [2]$$

or for chamber pressure as:

Presented at the 1950 Annual Convention of the AMERICAN ROCKET SOCIETY, Hotel Statler, New York, N. Y., Dec. 1, 1950.

$$\frac{P_c}{P_{cd}} = \left[\frac{F}{F_d} + \frac{P_a A_e}{F_d}\right]\left[\frac{F_d}{F_d + P_{cd}A_e}\right] \quad [3]$$

These equations have been plotted in Fig. 1 around a design chamber pressure of 400 psia and an ambient pressure of 14.7 psia. It is interesting to note the simple relationship between thrust and chamber pressure as illustrated by Fig. 1 and in particular the effect of altitude on thrust, this effect being a simple added thrust which is constant for all operating thrust levels. For example, if the sea-level design thrust is 1000 lb, the thrust at 50,000 ft will be approximately 1100 lb. If this same thrust chamber is throttled to 500 lb thrust at sea level, its thrust at 50,000 ft would be 600 lb. Note the constant 100-lb increase in thrust at both operating conditions.

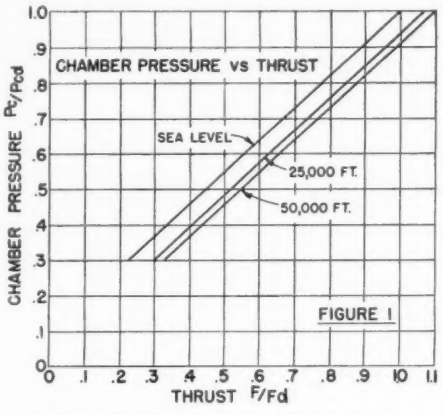


FIG. 1 CHAMBER PRESSURE VERSUS THRUST

The lower limit to which these curves apply is a function of the design conditions selected as well as the original assumptions of constant temperature and mixture ratio. For example, if the design conditions call for ideal expansion at sea level, overexpansion of the gases in the nozzle will occur as thrust is reduced. The effect of increasing altitude, however, will be to underexpand the gases in the nozzle. Since considerable variation from ideal expansion can be tolerated without undue loss in over-all performance, this condition does not appear to be serious for throttled thrust-chamber operation as low as 50 per cent or even less. In the event that refinement is desired, this can be accomplished by means of a nozzle in which expansion ratio and even throat size is controllable. However, the increase in complexity may not warrant its use in light of the relatively small gain to be expected.

Again assuming constant combustion temperature and constant mixture ratio, the propellant flow rate can be shown to be directly proportional to the absolute chamber pressure, or in terms of design conditions, as:

$$\frac{P_c}{P_{cd}} = \frac{W}{W_d} \quad [4]$$

The relationship for thrust in terms of propellant flow then becomes:

$$\frac{F}{F_d} = \frac{W}{W_d}\left[1 + \frac{P_{cd}A_e}{F_d}\right] - \frac{P_a A_e}{F_d} \quad [5]$$

or for propellant flow in terms of thrust as:

$$\frac{W}{W_d} = \left[\frac{F}{F_d} + \frac{P_e A_e}{F_d}\right]\left[\frac{F_d}{F_d + P_{ed} A_e}\right] \quad [6]$$

As is readily apparent from the simplicity of Equation [4], Equations [5] and [6] are similar to Equations [2] and [3], respectively. Again this is true of Fig. 2 with respect to Fig. 1. However, in this case more variation from the idealized theoretical result can be expected in actual practice since constant combustion temperature and mixture ratio will likely not be experienced under all operating conditions. These factors will have a greater effect here than on the chamber-pressure-versus-thrust relationship. In practice this results from a departure from the idealized propellant-flow-versus-chamber-pressure relationship indicated by Equation [4]. Assuming optimum performance at the design condition, performance as indicated by the dotted line in Fig. 2 might be expected in actual practice. This is an obvious result since maximum performance would be sought for at the design condition. Since Fig. 2 is based on design conditions, any departure at other operating conditions would be in the direction of increasing propellant consumption.

Variation in combustion efficiency and temperature is probably most affected by injector-design configuration and, in some cases, the means used for cooling the thrust cylinder. Under the idealized conditions shown in Fig. 2, it is apparent that the pressure drop through the injector at about half thrust will be only about 30 per cent of that obtained during full-thrust operation, resulting in quite different injector characteristics. In the more practical case with higher than the ideal flow at this same throttled condition, as illustrated by the dotted line, the injector drop is reduced to approximately 35 per cent of that at full thrust.

Where a turbine-pump system is used for supplying propellants to the thrust chambers—and most systems used in aircraft do use such a system—provision must be made for controlling the power input to the turbine in a manner which will compensate for the change in pump load. This can be accomplished by means of a pressure regulator which senses pump-discharge pressure and controls the quantity of propellant to the gas generator. Where a single propellant is used, this may be accom-

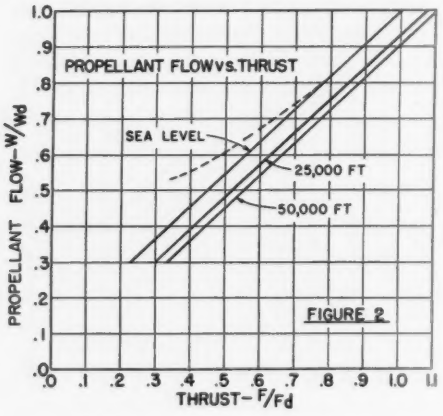


FIG. 2 PROPELLANT FLOW VERSUS THRUST

plished in a relatively simple manner. In the case of a monopropellant such as hydrogen peroxide for gas generator operation, the gas temperature is controlled by the concentration of the propellant used which is fixed in advance and the power input to the turbine by the mass flow into the gas generator. In the event that the monopropellant selected is not the same as that used for thrust-chamber operation, extra tankage would be required for the aircraft with its added complication. Where two propellants are used, the pump-drive control system becomes somewhat more complex. However, it does lend itself to use of the same propellants used for thrust-chamber operation and control of both the temperature and mass flow of the gases delivered to the turbine. This might be accomplished by controlling the actual flow of each propellant individually with suitable tolerance on mixture ratio and compensation for propellant temperature, or by controlling one propellant in a manner which will control the pressure delivered from the pump—or gas generator—and the other propellant in a manner which will control the temperature of the gases to the turbine.

In a variable-thrust system several means for controlling the flow of propellants to the thrust chamber can be used. Where a turbine-pump system is used to supply propellants, the pump-outlet pressure can be controlled as required to establish the desired propellant flow. Any system such as this would require rather careful matching of pump-output characteristics and orificing between the pumps and the thrust chamber to maintain satisfactory mixture ratio at all operating thrust levels. A more promising system provides for independent control of each propellant to each thrust chamber. In this manner, differences in pressure drop between the

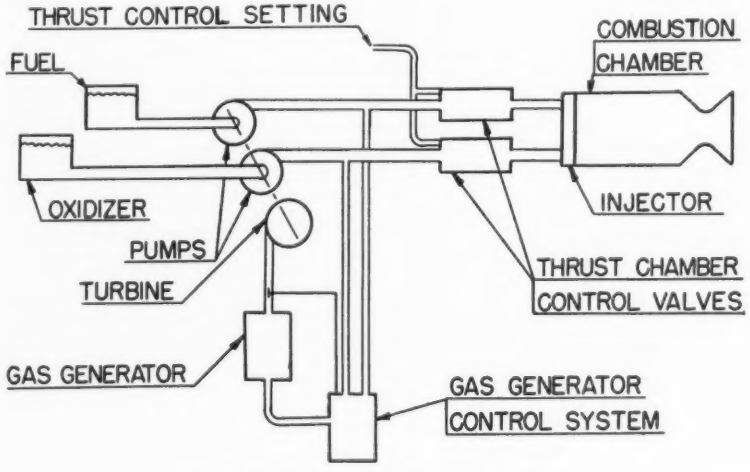


FIG. 3 THROTTLEABLE ROCKET POWER PLANT

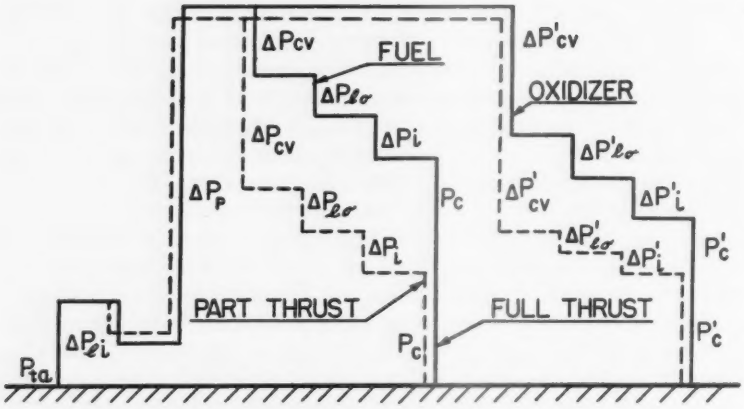


FIG. 4 PRESSURE DISTRIBUTION OF ROCKET POWER PLANT

pump and the chamber and differences in pump characteristics are automatically compensated for by the propellant-flow control valves and regulators. Fig. 3 is indicative of a system of this type. Fig. 3 shows the relationship of all the basic elements of the system to the complete system, i.e., tanks, pumps, turbine, gas generator, gas-generator controls, thrust-chamber control valves, injector, and thrust chamber.

For this system and based on the sum of all total pressures (velocity plus static heads) being zero around the complete system, the following equation can be written for full and part-thrust operation for each of the propellants.

$$\Delta P_{cv} = P_{ta} - \Delta P_{li} + \Delta P_p - \Delta P_{lo} - \Delta P_i - P_c \quad [7]$$

In this equation P_{ta} and P_c must be referenced to the same ambient, i.e., both psig or both psia. Fig. 4 is indicative of this pressure distribution under full and part-thrust operating conditions. The throttling effect of the thrust-chamber propellant-control valves for part-thrust operating conditions is clearly shown by the increased pressure drop indicated at the lower propellant flows required. If an added link is provided in the complete system, this large pressure

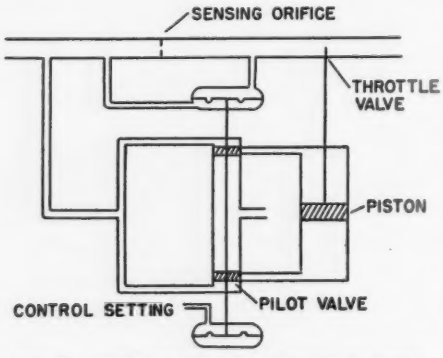


FIG. 5 SCHEMATIC SKETCH OF THRUST-CHAMBER CONTROL VALVE

drop can be somewhat reduced by operating the pumps at a lower pressure level for throttled thrust-chamber operation. Where turbine-exhaust gases are not recovered and used in some useful manner, this would result in a small increase in over-all efficiency of the power-plant system.

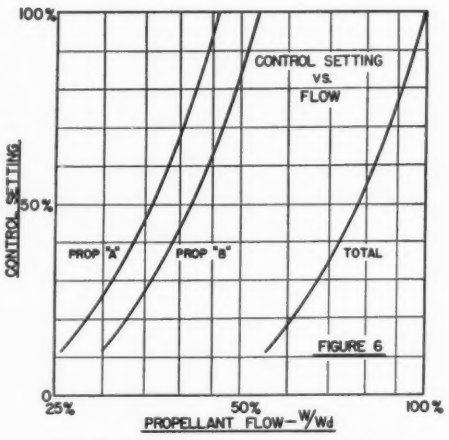


FIG. 6 CONTROL SETTING VERSUS FLOW

The thrust-chamber control valves serve the dual purpose of throttling propellants and as main shut-off valves. Fig. 5 shows schematically the function of these valves. The throttling piston is actuated from a four-way valve which is in turn actuated by the difference between the pressure drop across an orifice and some reference pressure. When the propellant flow becomes either greater or less than that required to maintain the four-way pilot valve in its equilibrium position, propellant is admitted to either the opening or closing side of the valve piston, thus opening or closing the main propellant valve as required to restore equilibrium operating conditions.

Fig. 6 is typical of flow obtained versus control setting of the regulator. It is apparent that with a flow-control system of this type, several methods of controlling thrust may be used either by manual control of the regulator setting, automatic control of this setting through a device sensing thrust-chamber pressure, or even some other related variable such as airplane velocity, etc. This becomes a subject in itself and no attempt is being made to cover it in this paper.

In closing it can be said that throttling thrust-chamber control using liquid propellants should considerably augment the utility of rocket power plants in piloted aircraft as well as possibly pilotless aircraft.

THE history of rocket research prior to and during the Twentieth Century is covered in two articles by Joseph W. Siry, head of the Theoretical Analysis Section of the Naval Research Laboratory's Rocket Sonde Research Branch. The articles were published in the November and December issues of *The Scientific Monthly*. Development of Greek fire, a composition of sulphur, pitch, resin, and crude saltpeter, used by Alexander the Great, was one of the first milestones in rocketry, he said.

THE NAVAL AIR ROCKET TEST STATION—PURPOSE AND PROGRESS

By Lieut. Comdr. F. C. Durant, III, U.S.N.R.

Mission, function, and reason for choice of site are explained. Existing and planned facilities at Lake Denmark, N. J., are described.

THE Naval Air Rocket Test Station is a field activity of the Navy Department, Bureau of Aeronautics. Its primary mission is to test and evaluate rocket engines, their components and propellants. The Aeronautical Engine Laboratory at Philadelphia, Pa., and the Aeronautical Turbine Laboratory at Trenton, N. J., fulfill the same functions for the Navy with regard to reciprocating and turbojet engines.

Need for Rocket-Engine Test Facility

In the early days of rocket-engine development, five or six years ago, contracts were loosely written because both the government and the contractors were in a new field. Little was known of the details of combustion of rocket propellants or the materials required in the construction of a rocket engine. Performance was conjectured. Combustion-chamber geometry was an art. In the design of injectors, relationships of hole diameter, tolerances, mixing, atomization, Reynolds' number, and cavitation were estimated. Final design was a balance between guesswork and ability of the machine shop. Bourdon tube gages and slow-response chart recorders did not yield data of sufficient accuracy for design purposes. "Cut and fit" was the order of the day. This method of design produced some surprisingly good fast-flying hardware but did not permit scaling with assurance to larger sizes. During these early contracts, scientists and technicians gained valuable experience and knowledge which was disseminated among the contractors. Gradually, techniques of tests were improved, rapid response instrumentation was developed, and reproducible data became available for reference. The rocket-engine manufacturers today receive contracts with specifications of increasing stringency.

During these early years, government acceptance tests generally were conducted at the contractor's plant using his instrumentation while observed by a government representative. The inadequacy and lack of standardized instrumentation on these tests made their value doubtful. It was therefore considered desirable to establish government facilities at which government personnel could test these engines to specifications using stand-

Presented at the 1950 Annual Convention of the AMERICAN ROCKET SOCIETY, Hotel Statler, New York, N. Y., Nov. 30–Dec. 1, 1950.

ard methods of instrumentation. Such tests would serve as a basis of comparison between engines of various contractors, and would be conducted without prejudice or bias. Besides contract specification tests, the Navy desired to evaluate completely the performance of "hardware" items. Taking a given engine, what exactly are its limitations with respect to ambient temperature and altitude? How many repeated runs will an engine stand without maintenance? Is an ignition system "sure-fire" after six months' storage? How many cycle operations will mechanical actions in pressure and flow regulators stand before malfunction? What are the effects of extreme ambient temperatures on propellant valve action? What effects do attitude and altitude exert upon engine performance? What is the difference in rate of corrosion of white fuming nitric acid stored at −60 and +170 F? The answers to these and many similar questions would serve as guides to the limits of specifications in new contracts. The result would be more rapid development of increasingly superior rocket engines.

Besides such test and evaluation needs, another major purpose in establishing the Rocket Test Station was to provide test facilities to rocket-engine contractors or government activities with inadequate or insufficient test facilities of their own. This refers in particular to the test stands required for engines of thrust greater than 10,000 lb. The normally high cost of construction of rocket-test stands and outfitting them with tankage and instrumentation rises rapidly with thrust capacity. In addition, some contractors are located so near to habitation that firing tests of really large engines are precluded because of public nuisance.

The furnishing of test facilities is not restricted to Naval activities or contractors but to any Department of Defense activity or contractor. In this manner, the Rocket Test Station serves as a pool of rocket-engine static-test facilities. Normally, office space and desks, local telephone service, workshop space (including common machine tools), certain expendable materials such as rocket propellants, standard test equipment, portable crane service, heavy rigging equipment, and propellant-transfer trucks or carts will be provided. Steam heat, electric power, water, sanitary facilities, locker space, fire protection, and physical security also may be made available. Delineation of all materials, accommodations, facilities, and services would be made a portion of the contract concerned. Assignment of facilities is made by the Bureau of Aeronautics in accordance with current work load and relative priorities. Assignment of rocket-test stands including tankage and instrumentation, if feasible and desired, will be made on a relatively long-term basis. In so far as practicable, assignment of facilities will be made in the same general area to one contractor to assure maximum operational efficiency and in consideration of contractors' proprietary rights concerning specialized operating techniques.

In addition to the above functions, the Chief of the Bureau of Aeronautics has directed the Commanding Officer of the Rocket Test Station to be pre-

pared to: (*a*) Undertake test and evaluation projects concerning rocket propellants; (*b*) develop test equipment necessary for instrumentation and test when such is not commercially available; (*c*) make investigations of ideas, devices, and propellants in order to provide a basis for future program planning; (*d*) provide engineering services in connection with flight-test projects (piloted or unpiloted) concerned with rocket engines; (*e*) assist the Bureau of Aeronautics in preparation of programs, detailed requirements, and specifications for rocket engines, their components, propellants, and associated equipment; and (*f*) train service personnel in the handling, servicing, and operation of rocket engines, their components, and associated equipment.

The last indicated function will provide a nucleus of service personnel in the fleet who are familiar with this breed of engine. When the time comes to form missile launching or loading teams, the background of practical experience acquired by these men will permit rapid and effective operational training.

Why Lake Denmark?

Upon realization of the need for such an activity, an extensive search was made to determine a desirable location. At Lake Denmark, Dover, N. J., was found an ideal site. Here, the Naval Ammunition Depot, established in 1895, was being deactivated. Available were some 650 acres of rolling timberland, miles of paved roads and railroad track, military housing, and dozens of warehouses suitable for conversion and use as shops, laboratories, and administrative buildings. Here, the Navy had already invested funds in rocket-test facilities presently being leased by a civilian contractor, Reaction Motors, Inc. The terrain at Lake Denmark is ideal for testing; remote from inhabited buildings, yet linked by highway and rail to metropolitan New York and New Jersey. Thus, a great saving in funds was effected in being able to utilize these ordnance facilities. Lake Denmark lies 35 miles west of New York, N. Y., and is within 300 miles of a number of major rocket-engine manufacturers. In addition, the Rocket Test Station is within easy flying distance of military technical headquarters: 1 hr to Washington; $2^1/_2$ hr to Wright-Patterson Air Base, Dayton, Ohio.

To map a master program of development of this site, the M. W. Kellogg Company, New York, N. Y., was employed to make an extensive engineering study. Ten volumes of drawings, layouts, and cost estimates were obtained. An estimated figure of $14,500,000 was whittled down to $7,500,000. In turn, this program was approved by the Naval Aeronautical Board, the Department of Defense Research and Development Board, and finally authorized by Congress and the President in 1950. An appropriation bill is currently pending. These funds will be used to expand and modernize existing test facilities, provide for purchase of more land to integrate present holdings, improve and standardize instrumentation, provide

an underground propellant-storage system, additional military housing, and outfitting of specialized shops and laboratories. This program will integrate and improve certain utilities, overage, inadequate, or over-extended. However, even without this long-range program, the Rocket Test Station is today a going concern.

Naval Aeronautical Rocket Laboratory

Starting as the Naval Aeronautical Rocket Laboratory at the Naval Ammunition Depot in July, 1948, a basic organizational structure was planned and approved by the Bureau of Aeronautics. Following the pattern of other military laboratories, the administrative posts in all departments are held by officers, generally with a civilian assistant to provide continuity when routine military transfers occur. In addition to this nucleus of officers a number of enlisted personnel are assigned for rocket training and housekeeping tasks. A detachment of Marine personnel provides physical security for the station. The bulk of the personnel at Lake Denmark, however, are civilian.

Naval Air Rocket Test Station

In April, 1950, the Naval Ammunition Depot was officially disestablished; management control shifted from the Navy Bureau of Ordnance to the Bureau of Aeronautics; and the name of the Rocket Laboratory changed to its present title of U. S. Naval Air Rocket Test Station under a commanding officer. Certain storage facilities, however, are still made available to the Bureau of Ordnance for inert materiel. As in all similar test activities, the three component parts, organization, personnel, and facilities had to be provided for and integrated. Starting from "scratch," organization lines, operating rules, and procedures were established.

It was recognized that the initial nucleus of engineering personnel drawn from academic life and industry had to be of the highest caliber. Hundreds of applications were screened and personal interviews held. Simultaneously, interim machine shop, propellants, and instrumentation laboratories were laid out, staffed, and equipped. New rocket-test stands together with tankage, instrumentation, and supporting utilities were constructed and checked out. Training programs were established to acquaint Navy aviation mechanics, electricians, and electronics technicians with the problems of rocket-engine operation, maintenance and servicing, instrumentation, and handling of propellants. Station utilities such as telephone systems, additional water supply for drinking and fire protection, replacement of worn-out transportation equipment, extension of electrical power lines, and so on, provided problems if there was a lull in project work.

The first projects were assigned, studies made, tests run, data recorded

and reduced, reports written, and the end product, evaluations and recommendations, have been made and reported.

Technical Projects

The following specific projects are typical of those currently assigned:

1 *Project 201. Development of Methods and Equipment for Testing Liquid-Propellant Rocket Engines.* This project covers work on specific problems not covered in other projects but necessary in the performance of the station's mission. Examples of these tasks are: (1) Integration of strip chart recording null balance potentiometers, end instruments, and three control consoles by means of a jack panel using cross-connecting plug-fitted leads; (2) investigation of a method for timing high-speed motion pictures of rocket jet flames; (3) design of transfer equipment to handle rocket propellants in tank car quantities from rail head; (4) obtain data to determine relative effect of distance and water-spray cooling on a rocket jet (this information is to be capable of scaling and is to be used in test stand design); (5) investigation of a method for recording chamber-pressure transients; and (6) development of specifications for portable fuel and oxidizer transfer carts.

2 *Project 501. Evaluation and Development of Ignition Delay Measurement Equipment for Self-Igniting Propellants.* The importance of short ignition delay is well known. Since desirable delays are generally less than 20 msec, unique methods of measurement are required. A number of different mechanisms and techniques are presently employed at different government-sponsored activities engaged in this work. The purpose of this project is first to review these various methods and techniques, attempt correlation, and finally make recommendations for standardization. Samples of the same batch of certain standard propellants are being made available to these laboratories for test, using their local method. From the interest exhibited by the various agencies, it is believed that fairly complete data will be obtained.

Some other current projects which may be referred to generally include: (1) The investigation of additives to rocket propellants to improve temperature or corrosion characteristics; (2) design of special-purpose rocket-test stands; (3) evaluation of specifications and bid proposals for engine-development programs; (4) evaluation of relative advantages of solid versus liquid-propellant engines for the power plant of a specific missile; and (5) thorough evaluation of performance of a rocket power plant under a wide range of operating conditions.

Summary

Thus, it is believed that the Naval Air Rocket Test Station fills a definite need in the Navy's testing and evaluation facilities. Here, the Navy may

obtain accurate test and fair evaluation of rocket engines, associated components, and propellants. By virtue of the facilities at hand and current practical experience, the station is able to make recommendations to the Bureau of Aeronautics in regard to specifications for contracts relating to future development and procurement in this field.

In a larger sense, the Rocket Test Station will provide a centralized pool of rocket-engine test facilities. Test stands with the highest quality instrumentation together with supporting utilities will be made available to Defense Department contractors as necessary. This is particularly important with respect to the testing of rocket engines in the high and very high thrust ranges. In these cases the government would otherwise be forced to provide funds to construct such test stands on contractors' property, re stricting future freedom of choice of contract in this field. The contractor gains by this method of test because he is completely relieved of responsibility for design, construction, and maintenance of such expensive facilities. Costs of liaison and transportation offset this advantage to a minor degree.

The Rocket Test Station is a new activity. Its growth and development will be affected by the extent of national defense programs. It is expected that Lake Denmark will play a significant role in competent test and evaluation of rocket engines. By these evaluations future engines will become increasingly reliable and eventually will take their place in the services in operational use.

OPPORTUNITIES IN ROCKET ENGINEERING

WITH a greatly expanded test and development program for rocket engines starting to unfold at the U.S.A.F. Experimental Rocket Engine Test Station, Edwards Air Force Base, Muroc, Calif., immediate opportunities are open for mechanical, chemical, and electrical engineers. Exceptionally fine positions, offering opportunity for rapid advancement, are open to young engineers with ability. This growing organization also offers attractive propositions to experienced men in these fields.

Specialized training courses will be available to round out the engineering education of applicants with appropriate backgrounds who lack rocket experience.

Positions are also open for experienced rocket-propulsion technicians, test-stand foremen and mechanics who are experienced in rocket-test and development work.

Engineering positions will pay up to $6400 a year, depending upon experience and education. Hourly paid employees will obtain top wages based upon existing wage scales in the test center's area. A new housing project, including 550 homes and 174 one- and two-bedroom apartments, will be completed at Edwards Air Force Base this summer.

Persons interested in further information should get in touch with the Civilian Personnel Office at Edwards Air Force Base, Muroc, Calif.

EXPELLANT BAGS FOR ROCKET PROPELLANT TANKS

By W. R. Sheridan

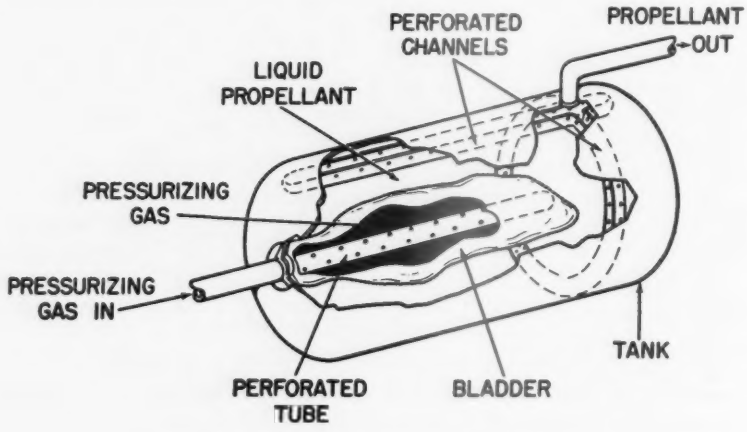
Rocket Section, Bell Aircraft Corporation, Buffalo, N. Y.

IN small liquid-propellant rockets, the propellant is customarily forced from the tank to the rocket motor by means of gas pressure.

In the operation of guided rockets against aircraft or other rapidly moving targets, it may be necessary for the missile to make sudden turns. If this should occur while the tanks are only partly filled with propellant, the motion of the missile will throw the liquid to one side of the tank, and may uncover the outlet and interrupt flow of propellant to the motor.

To prevent this from occurring, it is usual to introduce the gas into a collapsed bag or "bladder" contained in the tank of liquid. The bag unfolds or expands as the gas enters it, and forces the liquid from the tank. As the gas and the liquid are separated by the bladder it is impossible for any gas to enter the propellant lines until all the liquid has been expelled and the bladder bursts. This insures a continuous supply of propellant to the motor, regardless of the position or direction of the missile or the accelerations acting on it.

In order to prevent a portion of the liquid from being sealed off and trapped in one end of the tank, it is necessary to equip the walls of the tank with internal channels leading to the outlet.



DETAILS OF EXPELLANT BAG FOR PROPELLANT TANKS

Presented at the 1950 Annual Convention of the American Rocket Society, Hotel Statler, New York, N. Y., Nov. 30-Dec. 1, 1950.

Attaching the bladder to the pressurizing line is usually not a great problem, as the fittings can be made of stainless steel and the bladder attached by clamping, with or without an "O" ring seal.

Thought must be given to the stresses acting on the bladder at the point of attachment. Any forces acting on the bladder may be concentrated here, and may require a thickening of material in this region. Also, some bladder materials tend to cold flow, and this must be kept in mind when designing the bladder attachment.

Since the bladder is to be installed in the propellant tank in a folded or collapsed condition, its bulk subtracts from the amount of liquid which the tank can contain. Material which is of light gage and easily folded is therefore desirable. The gage, however, must not be so light that there is danger of the bladder tearing or rupturing when the gas pressure is suddenly applied, or when the missile makes a sudden turn.

In this connection, it has been found advantageous to have a perforated tube of some inert material, such as stainless steel or polyethylene, attached to the fitting inside the bladder to distribute the pressure of the incoming gas.

Another purpose served by such a tube is to position the bladder in the tank. A little consideration will show that if the bladder is compacted at one end of the tank it will have to unfold or expand its way to the other end. In this process it may become bound against the tank wall by pressure, or impeded by channels, bosses, or other internal fittings. If the internal diffuser tube is made nearly as long as the tank, and the bladder folded around it, only a sidewise unfolding will be necessary, since the bladder is already positioned the full length of the tank. The method of folding is important, and must allow the bladder to open without binding or becoming tangled in itself.

The material used for bladders must meet exacting requirements. First of all it must be compatible with the liquid in which it is used. It must neither be attacked appreciably by the liquid during the time of contact, nor cause decomposition or other harmful change in the propellant. It must be compatible over the entire range of temperature to which the loaded rocket may be subjected in storage or service.

It is of course desirable that the bladder material be readily available and inexpensive.

Temperature may introduce some embarrassing problems. For example, materials which are affected only slowly by fuming nitric acid at ordinary temperatures may be attacked rapidly if the rocket is stored under conditions of extremely high temperatures. Again, a material satisfactory at room temperature may be a complete failure at −40F or even at −20F due to stiffening and brittleness.

Sometimes the low-temperature requirement may be modified if the liquids have relatively high freezing points, like aniline and hydrogen

peroxide. In this case there is obviously no need to develop a bladder material which will be flexible below the freezing point of the propellant.

Bladders are often fabricated from sheet materials, for example, by means of adhesives. Adhesives used must also be compatible with the liquid and be serviceable over the entire temperature range.

In the case of certain materials, for example, Vinylite and Kel-F, it is possible to avoid the use of adhesives by heat-sealing or electronically sealing the pieces together. When rubber, either natural or synthetic, is used, the bladder can be made in one piece by dipping from latex.

An interesting example of bladder development resulted from the need for an expulsion bladder for use in liquid oxygen. Oxygen boils at −298F under atmospheric pressure, and the ordinary gas-tight materials, such as rubber and plastics, are hard and brittle at this temperature. With fibrous materials this difficulty is not encountered. For example, both cotton and nylon cloth are quite flexible in liquid oxygen, but cannot be used because they are not gas-tight. Any attempt to impregnate them involves the use of a material which is not flexible in liquid oxygen.

After testing literally hundreds of samples, a satisfactory bladder was finally made from semifinished glove leather (goat skin) coated with a commercial resinous adhesive, which in thin layers remained fairly flexible in liquid oxygen. The same adhesive was used on the seams of the leather bag. Although the resulting bag was not completely impervious to gas, its permeability was reduced to such an extent that the amount of gas lost during the running time of the rocket motor was quite small.

In regard to the criterion of availability mentioned previously, it is interesting to speculate as to whether a large demand for liquid oxygen bladders of this type would result in goats going on the list of critical strategic resources. At any rate, it is startling to think of the goatherder contributing to the functioning of a rocket.

To summarize, an expulsion bladder is necessary for successful operation of a rocket which is required to maneuver in flight, but careful consideration must be given to the material, method of fabrication, and method of installation in the tank if it is to perform its function in a satisfactory manner.

Are Your Membership Fees Up to Date?

BECAUSE of the cost of production, it will be necessary to remove the names of all dues-delinquent members from the JOURNAL mailing list. What is the status of your dues?

MEASUREMENT OF THE BURNING RATE OF LIQUID PROPELLANTS

By C. W. Tait,[1] A. G. Whittaker,[2] and H. Williams[3]

MEASUREMENT of the burning rates of propellants to be used in rocket motors is an important problem. B. L. Crawford, Jr., and co-workers[4] have worked out a technique for measuring the burning rates of solid propellants, but little information has been published on the burning rates of liquid propellants. Therefore, the present work was carried out to extend the measurements to liquid-propellant mixtures.

In the case of liquid bipropellants, there are two classes of mixtures. One class is the hypergols, which ignite spontaneously when mixed, and the other class is the nonhypergols, which do not ignite spontaneously when mixed. The instrumental problem involved in measuring the burning rates of hypergols is a severe one and no information on this subject will be presented in this paper. The problem with nonhypergols is less severe, particularly in the case of miscible components. For obtaining the burning rates of such materials an adaptation was made of Crawford's technique for solid propellants. Crawford used a principle described by Muraour[5] which consisted of a direct determination of the time for a given length of strand of solid propellant to burn. Crawford improved the technique by inhibiting the grains with organic coatings to prevent the flame from spreading to the sides of the strands. Thus, the burning surface of the strands remained reasonably flat and normal to the axis.

In the present work, an attempt was made to use cellulose drinking straws reinforced with paraffin for holding the liquids. Burnings of such systems proved erratic. High-speed motion pictures showed that the burnings consisted of a series of minor explosions. When glass tubes were used to contain the liquid, the burnings became smooth and nonexplosive. Glass tubes, therefore, were used throughout the work being reported.

Description of the Apparatus

The tubes used to hold the liquid propellant were Pyrex glass tubes of nominal 7-mm OD and 5-mm ID. The tubes were 7 in. long and were sealed off at the bottom. The movement of the burning surface down the tube was measured by the fuse-wire method of Crawford. Holes

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Presented at the 1950 Annual Convention of the AMERICAN ROCKET SOCIETY, Hotel Statler, New York, N. Y., Nov. 30–Dec. 1, 1950.

[1, 2, 3] Chemists, U. S. Naval Ordnance Test Station, Inyokern, Calif.

[4] B. L. Crawford, Jr., et al., Anal Chem., 19, 630–3 (1947).

[5] H. Muraour and W. Schmacher, Mem. Poudres, 37, 87–97 (1937).

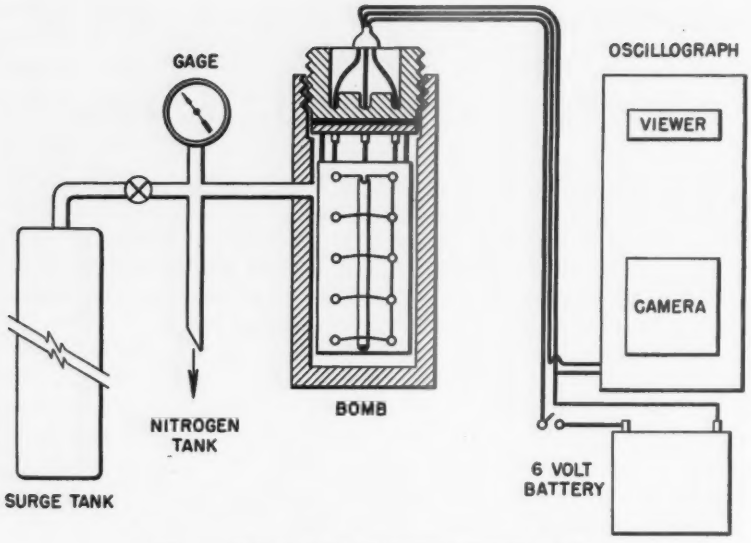

FIG. 1 APPARATUS FOR MEASURING BURNING RATES

were drilled in the tubes at 2-in. intervals and lengths of 0.5-ampere fuse wire were threaded through the holes. The wires were sealed in place with DeKhotinsky cement. The tubes were filled with liquid propellant to within 0.2 of an inch of the top and an igniter was fitted into the top of the tube just touching the liquid surface. The igniter consisted of a piece of No. 30 iron wire with a 0.25-in. length of 0.1-in.-diam ballistite threaded on the wire. The wire was bent in a U shape around the ballistite so that the igniter would fit inside the glass tube.

For making burnings as a function of pressure the propellant-filled tubes were placed inside a bomb similar to one described by Crawford. A schematic drawing of the equipment used in the present work is shown in Fig. 1. A plate with insulated electrical connectors was fastened to the screw head of the bomb. The fuse and igniter wires from the glass tube were fastened to these connectors. The leads were brought up the back of the plate through spark plugs to the outside of the bomb. The igniter was fired with a 6-volt battery. The same connection of the battery put 300 ma through each fuse wire, the high potential side of which was connected to a sensitive galvanometer in a multichannel oscillograph.[6] The galvanometers had mirrors which directed light beams on to photographic paper[7] in a motion-picture camera included in the oscillograph. When a fuse wire

[6] Type 5115 P4 Consolidated Engineering Corporation.
[7] Linograph paper No. 809 (7 inch × 125 feet).

was broken by the burning surface, a step was produced in the trace on the photographic paper. A mirror in the oscillograph permitted viewing of the traces during the run so the camera could be actuated manually. Timing marks were recorded automatically on the paper every 0.01 sec. Electrical timing clocks[8] were also used with the fuse-wire setup, the clocks being started by the breaking of the first wire and being stopped by the burning of subsequent wires. These two methods of timing checked each other.

Pressure for the bomb was obtained from commercial nitrogen cylinders. A Bourdon gage was used to read the pressure in the bomb. A 9-liter surge tank maintained the pressure constant to within 3 per cent during the burnings. The bomb was made pressuretight with an unsupported area seal consisting of a rubber washer below the threads on the bomb head. One bomb was equipped with a narrow Lucite window in front of the glass tube to permit photography of the burnings. The Lucite window was made pressuretight with an unsupported area seal.

Results of Burning Mixtures of 2-Nitropropane and Nitric Acid

The apparatus described above was used to determine the burning rates of mixtures of 2-nitropropane and white fuming nitric acid (98 per cent). Measurements were made over a range of pressure from 200 psia to 2000 psia with variation in a number of variables to test the significance of the method. The experimental data are plotted in Fig. 2, where burning rate in in. per sec is plotted versus absolute pressure. The effect of several physical variables will be discussed before considering the variation of burning rates with pressure.

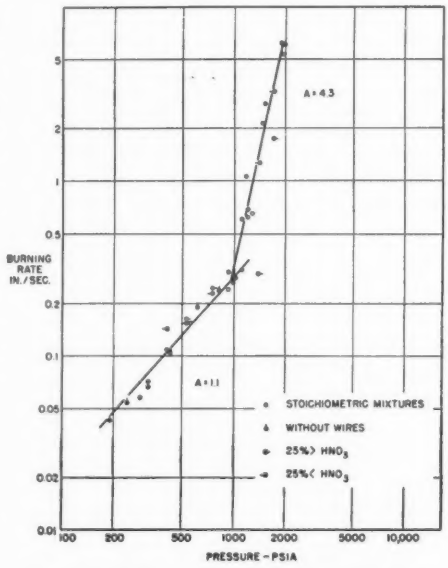

FIG. 2 BURNING RATE DATA FOR MIXTURES OF 2-NITROPROPANE AND NITRIC ACID

Effect of Igniter: It was not possible to ignite the mixtures of 2-nitropropane and nitric acid with a hot

[8] Type S1 clocks manufactured by the Standard Electric Time Company, Springfield, Mass.

TABLE I

BURNING TIMES FOR STOICHIOMETRIC MIXTURES OF 2-NITROPROPANE AND WFNA OVER 2" INTERVALS AT 1964 PSIA

	1st Interval	2nd Interval	3rd Interval
	0.335 sec.	0.320 sec.	0.355 sec.
	0.307	0.328	0.332
	0.324	0.312	0.320
Average	0.325	0.320	0.336

$\bar{x} = 0.326$ σ mean = 0.005

wire. It was necessary to fortify the wire with ballistite as described above in order to initiate burning. With the fortified igniter, burning was sustained at bomb pressures down to 200 psia. Burning was not sustained at 145 psia. It was felt that the fortified method of ignition was valid in view of the intended application of the data, namely in rocket-motor design.

Effect of Fuse Wires: The presence of the fuse wires had no pronounced effect on the burning rate over the pressure range studied. About one half of the data given in Fig. 2 below 900 psia was collected in tubes with fuse wires and the other half was collected in unpunctured tubes by photography. No systematic difference between the two sets of data was observed. At 2000 psia the agreement between the data from the two types of tubes was also good.

Variation of Rate with Interval: Another variable studied was the position of the measuring interval along the length of the glass tube. In Table 1 is shown the results of three burnings of 2-nitropropane and nitric acid at 1964 psia. The intervals were successive 2-in. intervals along the glass tube. The data showed good reproducibility although not as good as that reported by Crawford for solid propellants. The over-all accuracy of the data in Table 1 is probably ±3 per cent.

Table 2 shows data for the same system at a pressure of 1131 psia. In these data there were two modes of burning, one taking about 3 sec to burn 2 in. and the other about 6 sec. The change in mode took place during the burning as indicated by the results of the first and fourth burnings. From a statistical point of view the values for the two modes differed significantly. As shown in Fig. 2 the slower burning time appeared to be a continuation of the trend of the data in the low-pressure region. The faster burning time appeared to fit on the steeper slope of the high-pressure data. Therefore it was felt that the two modes of burning were real and that a change in mode took place during the burning.

TABLE II

BURNING TIMES FOR STOICHIOMETRIC MIXTURES OF 2-NITROPROPANE AND WFNA OVER 2" INTERVALS AT 1131 PSIA

1st Interval	2nd Interval	3rd Interval
3.05 sec.	5.54 sec.	6.51 sec.
6.23	6.56	6.18
3.76	3.13	3.20
3.12	3.23	6.51

Average of 3's = 3.25 seconds σ mean = 0.10
Average of 6's = 6.40 seconds σ mean = 0.10

Effect of Tube Diameter: The data in hand are not clear on the effect of tube diameter on burning rate. Tube-diameter effect was confused

by change in mode of burning during the runs. At 1500 psia, 8-mm and 7-mm OD tubes gave comparable results for the fastest mode recorded. Results with 6-mm tubes were 15 per cent lower and with 5-mm tubes about 40 per cent lower. Also a few results with 6- and 5-mm tubes showed a much slower mode of burning than the slowest mode obtained with 7- and 8-mm tubes. More work is needed to clarify the effect of tube diameter.

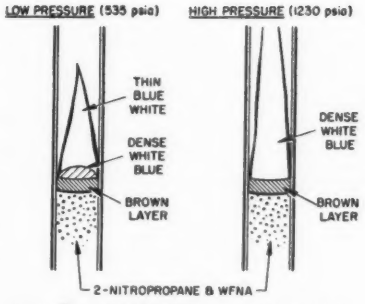

FIG. 3. APPEARANCE OF FLAMES IN BURNINGS OF 2-NITROPROPANE AND WFNA

Effect of Propellant Ratio: At pressures below 900 psia the burning rate was not sensitive to change in propellant ratio. Runs were made with 25 per cent by weight greater nitric acid than stoichiometric ratio and with 25 per cent less acid than stoichiometric. Up to 900 psia the results for these compositions agreed fairly well. At higher pressures the excess nitric acid slowed down the burning rate appreciably. The 25 per cent deficiency of acid did not appear to affect the rate at high pressures.

Effect of Bomb Pressure: The data in Fig. 2 of burning rate versus pressure can be represented fairly well by two straight lines on the log-log plot. The slope of the line is 1.1 in the low-pressure region and 4.3 in the high-pressure region. A slope of 1 is usually associated with a second-order reaction as the rate controlling step, whereas a slope of 4 is not encompassed by available theory.

It was also observed experimentally that the volume of the flame increased considerably with increase in pressure. Sketches of the flame for low and high pressures are shown in Fig. 3. At 535 psia three reaction zones were visible. The first zone was a thin brown layer, presumably containing NO_2 in the yellow liquid. The second zone was in the flame and was an opaque whitish blue color. The third zone was a transparent blue-white cone extending about 2 cm up the tube. At 1230 psia there were only two zones visible. The thin brown layer was still present in the liquid and an opaque whitish blue cone of flame extended 4 or 5 cm up the tube.

The character of the high-pressure flame and the burning-rate data suggest the possibility of another source of heat (other than the burning surface) for vaporizing the propellants. It is conceivable that an otherwise negligible exothermic reaction becomes of importance in the liquid phase, and that this heat produces additional vaporization of the liquid. If the flame velocity is essentially constant, then the flame volume would have to increase so that stable burning can be maintained under the new conditions of a greater rate of fuel supply. The temperature, and hence the pressure,

at which this exothermic reaction becomes appreciable could be quite specific, thus accounting for the sharp transition in the burning-rate data.

To follow up on the possibility of liquid phase reaction, measurement of the temperature below the burning surface and a study of high temperature and pressure reactions of the propellants will be undertaken. Such an approach should define whether it is feasible for a liquid phase reaction to occur in this system and to cause the observed change in character of the burning rate data.

Conclusions

The data presented indicate that an established technique for determining burning rates of solid propellants can be adapted to liquid propellants. Burning rate data collected in 7-mm glass tubes had a standard deviation of the mean value of 1.5 per cent.

Measurements with mixtures of 2-nitropropane and nitric acid showed that the burning rate increased with the 1.1 power of pressure over the pressure range from 200 to 1000 psia and with the 4.3 power over the range from 1000 to 2000 psia. In the transitional region, burning on occasion changed from the rapid to the slower mode during the burning.

Future work will attempt to measure the temperature beneath the burning surface and to define whether a liquid phase reaction could cause the observed change of character of the burning rate data at 1000-psia pressure.

American Rocket Society News

Six Excellent Papers Scheduled for ARS Toronto Meeting

THE technical program of the American Rocket Society at the Semi-Annual Meeting of The American Society of Mechanical Engineers to be held at the Royal York Hotel, Toronto, Ontario, Canada, June 11–14, 1951, will consist of two sessions during which six papers will be presented. The tentative program follows:

Monday, June 11

9:30 a.m.

"Rocket Applications of the Cavitating Venturi" by L. N. Randall, rocket test supervisor, Curtiss-Wright Corporation, Propeller Division, Caldwell, N. J. The principles of operation and details of construction of this interesting device are presented. Curtiss-Wright's development and application thereof to liquid rockets is described. It has been applied extensively as an extremely simple and accurate flow control. Its usefulness as a temperature measuring device is also outlined, as are special forms designed to meet particular requirements.

"Equipment for Handling High Strength, Hydrogen Peroxide" by Noah S. Davis, Jr., manager, Special Projects Department, and John H. Keefe, Jr., supervisor of special projects department, Buffalo Electro-Chemical Company, Inc., Buffalo, N. Y. A search was made for

the most satisfactory equipment for handling H_2O_2 in storage and propellant systems. The results of compatibility tests on various materials, including metals, plastics, and lubricants are presented. General equipment design considerations and methods of preparing the equipment for H_2O_2 service are outlined. Examples of the following equipment are presented and discussed: pumps, containers, piping, flexible hose, valves, and reactors.

"Optical Methods of Rocket Motor Evaluation" by Kurt Stehling, Bell Aircraft Corporation, Buffalo, N. Y. The various classical methods for evaluation of rocket motor parameters are outlined briefly. New methods such as "optical" which are gaining favor in view of the requirements of refined rocket motor design are discussed, including types of instruments, methods of analysis and specific applications (measurement of exhaust and chamber flame temperature, of combustion flame front configuration, and distribution, combustion patterns, and injector and spray studies).

2:30 p.m.

"Materials for Use in Uncooled Liquid Propellant Rocket Motors" by W. R. Sheridan, Bell Aircraft Corporation, Buffalo, N. Y. This paper introduces basic materials requirements for refractory liners, outer shells and cements; illustrates the results of tests; and establishes the general range of applications which it is expected that uncooled motors can fulfill.

"Successful Engineering of Ceramic Lined Rocket Motors" by H. Z. Schofield, supervisor, and W. H. Duckworth, assistant supervisor, ceramic division, Battelle Memorial Institute, Columbus, Ohio. Ceramics are believed to have a definite future in rocketry if properly exploited. From the results of service tests it appears that sound engineering practices can remove observed shortcomings of uncooled linings in most cases. The design and material problems are discussed in detail and several interesting new developments are described.

"Silicon-Carbide Linings for Uncooled Rocket Motors" by K. C. Nicholson, supervising engineer, research and development department, The Carborundum Company, Niagara Falls, N. Y. This is one of the more promising liner materials. The development thereof by the Carborundum Company is described and engineering information pertinent to the application of this material is presented, including ranges of available sizes and shapes, methods of fabrication and installation. Information permitting an economic comparison of motors constructed with materials of this type with cooled motors is presented.

ARS Preprints

PAPERS to be presented at the Semi-Annual Convention to be held in Toronto, Canada, are available from the Secretary of the American Rocket Society, 29 West 39th Street, New York 18, N. Y. Members 25 cents, nonmembers 50 cents.

ARS New York Section

AT THE regular meeting of the New York Section of the American Rocket Society held in the Engineering Societies Building, March 16, 1951, Dr. Frank Parker, director, Project SQUID, Princeton University, discussed the subject "Research and its Relation to Jet Propulsion Development" before an audience of 75 members and guests. Mr. Lee J. Bregenzer, director of the New York Section, presided.

While jet-propulsion development is a responsibility of the engineer, Dr. Parker said, the scientist has much to contribute by applying research to the solution of practical problems. The scientist can accelerate advances in the field by (1) investigating phenomena known to occur in jet engines to provide a better understanding of what actually occurs; for example, what happens in the cooling of turbine blades or just how do solid propellants burn; (2) by accumulating data on thermodynamic properties of gases; and (3) by evolving new systems of jet propulsion. Dr. Parker described some recent

research in the phenomena of burning to show how new knowledge could help designers. Actual development of jet engines however was not the job of the universities which must limit their work to factors that contribute to design.

Refreshments were served at the conclusion of a question and answer period.

Dr. Crocco Speaks

An interesting paper on "Aspects of Combustion Stability in Rockets" was presented to the New York Section on April 20, 1951, by L. Crocco, Goddard Professor, Guggenheim Jet Propulsion Center, Princeton University. Dr. Crocco reviewed established theories covering unstable operation of combustion chambers with respect to propellant-flow variations under varying conditions of propellant system pressure drops. These established concepts were extended to show an added effect on combustion stability introduced by variations in the ignition delay time. Zones beyond which unstable combustion is certain with respect to pressure drop, ignition delay, and flow variations were developed.

Indiana Section

DESIGN and development of a jet engine was the topic under discussion when the ARS Indiana Section met on April 16, 1951, in the Mechanical Engineering Building, Purdue University. The speaker was John Wetzler, engine project engineer, Allison Division of General Motors Corporation.

Mr. Wetzler described the development of a jet engine, using as his outline a chart showing various phases, their sequence, time involved, and personnel required.

From the beginning establishment of need of the engine, through cycle analysis, blading design, and preliminary layout, he proceeded to stress analysis, the oil system, preliminary weight calculations, control design, and accessories choice. Intermediate layout, anti-icing, and productability preceded correlation with the aircraft manufacturer, probably the most time-consuming phase. He said final layout of the first test engine, detailing of purchasing scheduling, assembly tool design, test stand design and construction, description of component test equipment, recalculation of preliminary layout, stress analysis, and oil system to the final layout, and component tests all led to the dramatic first engine assembly and test.

The entire procedure from establishment of need to engine test usually takes 18 months. Mr. Wetzler observed that this period is not unusual. The engine, he said, was operated at 10–20 per cent speed, to show up certain difficulties.

As a result of the first tests refinements in design are begun. After ten 5-hour cycles the engine may still be running in spite of other difficulties. Redesign for production is commenced and at about the same time consideration is given to higher production models.

Mr. Wetzler stressed that careful attention should be given to early stages of development. This, he said, pays off in the end.

Mr. Wetzler graduated from the Johns Hopkins University in 1939. Following his graduation, he was test engineer at the General Motors Proving Ground and in 1941 was transferred to the Allison Division where he worked in the Test Department on piston engines and later on jets. In 1947 he was made head of the group responsible for the aero and thermodynamic design of axial-flow jet engines.

The Second Annual "Acceleration" Banquet was held on May 24. The main speaker was Dan S. Kimball, Under Secretary of the Navy. President H. R. J. Grosch was present as well as many other outstanding ARS members.

Southern California Section

THE SOUTHERN California Section of the American Rocket Society has been enjoying recently a sense of achievement because of the growing interest in the ARS among engineers, chemists, aerodynamicists, and others in southern California.

They report that their membership drive is gathering momentum. In the interval between January 1 and April 1 more than 41 new members joined the Section. The goal for 1951 is 200 more. Of significance is that the Section is attracting men who are designing, installing, manufacturing, and servicing rockets and allied systems.

More than 95 per cent of the present membership is actively engaged in the rocket industry.

In April the Section broke two records, which, like straws in the wind, indicate how things are going. On April 24, the Section sponsored a closed meeting at the Pasadena Athletic Club. The attraction was a dinner and a "Symposium of Propellant Selection." What happened exceeded all expectations. It turned out to be the largest dinner meeting and the largest classified meeting ever put on by the Section. Dinner was served to 137—some 50 others joined the audience to hear seven experts discuss every aspect of propellant selection at a technical level which was a source of pride to ARS officers.

The March meeting, which was not a closed meeting, was held in co-operation with the American Society for Quality Control. H. S. Seifert presided.

The first speaker was Chester Hylkema, Jet Propulsion Laboratory, who described the central recording system for the electrical instrumentation of rocket-motor tests. This system, he said, makes it possible for a single group of recorders to do the work of many motor-test sites. The system connects the test sites with the recording center by multipair lead-sheathed cable and enables remote control of recorders and remote indication of qualities being recorded.

Edward Cartotto of the Aerophysics Department of North American Aviation spoke on "Investigation of Instrumentation Performance with the C-Chart."

The C-Chart, he explained was a tool for statistical quality control of a produc-

ARS SOUTHERN CALIFORNIA SECTION HOLDS CLOSED MEETING PROPELLANT SELECTION

(*Left to right at table:* R. D. Geckler, assistant chief engineer, solid engine department. Aerojet Engineering Corporation; D. L. Armstrong, chief research chemist, Aerojet; M. T. Myers, group leader, North American Aviation Co.; D. A. Young, chief, rocket physics, Aerojet; R. B. Canright, president, ARS Southern California Section, and senior research engineer, Jet Propulsion Laboratory, California Institute of Technology; Carl Scheller, Air Materiel Command; L. C. Cole, research chemist, Jet Propulsion Laboratory; and T. F. Dixon, assistant to chief, propulsion research section, North American Aviation. In the foreground is Fanki Van Der Wal, aerodynamicist, Douglas Aircraft Company.)

tion process. It provided a means of judging the behavior of a quality-control system to indicate when quality level has deteriorated sufficiently to require corrective action.

All production systems, he said, were affected by two classes of events: Unpredictable events, random in nature to which no cause can be attributed; and assignable events caused by malfunction of some detail of the process.

The C-Chart was based on the Poisson frequency distribution. It could be applied only to processes which meet five essential requirements which he discussed in detail.

Engineers were slowly accepting the practical virtues of statistical analysis. Mr. Cartotto deprecated in jest the low estimate of workers in the field attributed to one publication which said, "Of all the children of Ananias, statisticians have traditionally been regarded as holding the foremost rank, even ahead of the liars and the damned liars."

Book Review

Assisted Take-off of Aircraft

REVIEWED BY THEODORE VON KÁRMÁN[1]

ADMIRAL Bolster's lecture for the James Jackson Cabot Fund is a very welcome contribution to aeronautical engineering literature, especially because this important field of aeronautical engineering, which was somewhat neglected in technical journals, has been treated by a man who is not only intimately acquainted with the problems and their solutions, but who also took an active part in sponsoring assisted take-off developments.

After an interesting introduction, the second chapter of the lecture gives a general review of the field of assisted take-off; the third chapter contains a complete story of catapult development, the problem with which Admiral Bolster was closely connected; the fourth chapter gives a sketch of the development of jet-assisted take-off; the fifth chapter deals with commercial applications of JATO. The sixth chapter is especially valuable, because it contains an excellent presentation of the take-off characteristics of airplanes equipped with JATO in a form and on a scientific level which is hard to find in previous publications. Finally, a short last chapter deals with the future of assisted take-off and gives a rather optimistic forecast of future progress.

Since the excellent lecture of Admiral Bolster certainly will be used as an important source of future writings, the reviewer believes that it will be helpful to the reader to amplify certain aspects of the historical account presented therein, particularly those developments with which this reviewer was associated.

The expression "historical data" may be applied in this case to events which occurred only 10 to 12 years ago, since the fast pace of engineering development in aeronautics has already given events of the last decade a historical character.

The Consolidated Aircraft Company was the first aeronautical organization which, to the knowledge of this reviewer, showed interest in jet-assisted take-off. The president, Reuben Fleet, recognized the importance of the problem, and asked the Guggenheim Aeronautical Laboratory at the California Institute of Technology (GALCIT) to recommend someone to prepare a report on the subject. Thus, in August, 1938, Dr. F. J. Malina submitted a report to the Consolidated Aircraft Company on the rocket motor as an auxiliary to the power plants of conventional aircraft.

Active work on assisted take-off in this country was undoubtedly initiated by General of the Air Force, H. H. Arnold, at that time Commanding General of the Army Air Corps. General Arnold asked the National Academy of Sciences in the

James Jackson Cabot Fund lecture by Rear Admiral Calvin M. Bolster, Norwich University, Northfield, Vt., Publication No. 9, 1950.

[1] Fellow ARS, Chief Consultant, Aerojet Engineering Corporation, Azusa, Calif.

fall of 1938 to form a committee for Air Corps research. In the first meeting of the committee, the General presented a number of problems whose solution in his estimation was urgent for the Air Corps and could best be studied by scientific institutions. Among many scientists from several institutions, Dr. R. A. Millikan and the writer represented Caltech and Dr. Hunsaker represented MIT. One of the problems was rocket-assisted take-off for bombers. Caltech volunteered for the study of this problem, while MIT took up the urgent problem of deicing of windshields. The writer remembers Dr. Hunsaker telling him, "You can have the Buck Rogers job."

As is mentioned in Admiral Bolster's lecture, an enthusiastic group of researchers at Caltech started to experiment with rockets already in 1936. The members of this group were F. J. Malina, H. S. Tsien, A. M. O. Smith, J. W. Parsons, E. S. Forman, and Weld Arnold. The latter also donated a sum of $1000 for experiments made by the group.

After the meeting with General Arnold, the National Academy granted the first contract, amounting to the staggering sum of $10,000 (coming from Air Corps funds), and the GALCIT Air Corps Jet Propulsion Research Project was born. The Project was under the writer's direction with Malina, Parsons, and Forman as first members of the Project. Dr. M. Summerfield joined the group in 1940. The contract covered both liquid and solid-propellant rocket development.

In 1940, on the initiative of Maj. Benjamin Chidlaw, the present Commanding General of the Air Materiel Command, the Air Corps assumed direct sponsorship of the GALCIT Project.

One of the necessary studies in the program was the equilibrium theory for restricted-burning solid-propellant rockets. It was worked out in 1940 by the writer and Malina, and it proved the possibility of stable burning and gave the criteria of stability as well.

The first flight tests with restricted burning rockets were made for the Air Corps on the Ercoupe Airplane in August, 1941. The propellant was a pressed amine powder, GALCIT 27, formulated by Parsons. The airplane was piloted by Capt. H. A. Boushey.

Following these tests early in 1942 the Bureau of Aeronautics of the Navy Department placed a contract at the GALCIT Project for the development of a solid-propellant rocket delivering 200-lb thrust for 8 sec (the first JATO unit). During the period of this contract, Parsons made the first tests on an asphalt-potassium perchlorate propellant known as GALCIT 53, which was utilized in the unit specified by the Navy.

This experimental unit was turned over for further development and production to the Aerojet Engineering Corporation which had been established, under the presidency of Andrew G. Haley, in the same year.

The development of liquid-propellant engines was pursued at the GALCIT Project simultaneously with the work on solid propellants. To the writer's knowledge, the use of nitric acid and aniline as a propellant combination was first introduced and tried at the GALCIT Project, on F. J. Malina's suggestion. The idea was stimulated by certain experiments on the reaction of these two liquids, carried out at Annapolis with a view to gas generation for pressurication purposes.

The first assisted take-off tests with two acid-aniline engines delivering 1000-lb thrust for 25 sec on the A-20A airplane were carried out for the Air Corps in April 1942 at Muroc, Calif., with Maj. P. H. Dane as pilot.

After 1943, the main field of activity of the GALCIT Project became the study of long-range rocket missiles. Work on solid and liquid propellant for assisted take-off rockets, especially engineering design and production, was carried out by the Aerojet Engineering Corporation, mostly under effective sponsorship of the Bureau of Aeronautics of the Navy Department. These phases of the development are described in a complete manner by Admiral Bolster.

1951 Guggenheim Fellows Announced

JOINT announcement was made recently by Harry F. Guggenheim, President of The Daniel and Florence Guggenheim Foundation, Dr. Harold W. Dodds, president, Princeton University, and Dr. Lee A. DuBridge, president, California Institute of Technology, of the appointment of seven new Daniel and Florence Guggenheim Jet Propulsion Fellows.

Recipients are: *Princeton*, Arnold Goldburg, Mahwah, N. J.; Marcus P. Knowlton II, Auburndale, Mass.; Lieut. D. M. Saunders, Takoma Park, Md.; and Marcel Vinokur, Long Island City, N. Y. *Caltech Center:* George E. Hlavka, Racine, Wis.; Robert C. Evans, Pittsburgh, Pa.; and Herman Carl Thorman, Berea, Ohio.

The Fellowships carry a stipend of $2000 annually, and are normally awarded for one year, but may be renewed for an additional year.

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